

Kepler Detected Gravity-Mode Period Spacings in a Red Giant Star

P. G. Beck,^{1*} T. R. Bedding,² B. Mosser,³ D. Stello,² R. A. Garcia,⁴ T. Kallinger,⁵ S. Hekker,^{6,7} Y. Elsworth,⁶ S. Frandsen,⁷ F. Carrier,¹ J. De Ridder,¹ C. Aerts,^{1,9} T. R. White,² D. Huber,² M.-A. Dupret,¹⁰ J. Montalbán,¹⁰ A. Miglio,¹⁰ A. Noels,¹⁰ W. J. Chaplin,⁶ H. Kjeldsen,⁸ J. Christensen-Dalsgaard,⁸ R. L. Gilliland,¹¹ T. M. Brown,¹² S. D. Kawaler,¹³ S. Mathur,¹⁴ J. M. Jenkins¹⁵

Red giants are evolved stars, representing the future Sun, and were recently discovered to oscillate in acoustic modes similar to those found in the Sun (1, 2). These modes are stochastically excited by convective motions in the star's outer layers and obey frequency spacing laws understood in terms of the theory of stellar oscillations (3, 4). These frequency patterns are used to derive the basic physical stellar parameters, such as the mass and radius, with unprecedented accuracy.

Unlike pure acoustic modes, mixed modes probe deeply into the interiors of stars, allowing the derivation of stellar core properties, such as the local density structure, the chemical composition gradient, and the near-core angular momentum, that would otherwise remain inaccessible.

We detected mixed modes in the red-giant star KIC 6928997 (Kepler Input Catalog) on the basis of 320 days of observations with the Kepler satellite (5). The oscillation spectrum of KIC 6928997 (Fig. 1) (6) deviates from the pattern expected for pure, short-lived acoustic modes (fig. S1). This indicates the presence of mixed

modes that have the character of a gravity mode in the core region and of an acoustic mode in the envelope of the star. From a theoretical perspective, modes with most of their energy in the core will not be observed because they get trapped there. However, in the case of dipole ($\ell = 1$) modes, the trapping is less efficient, and some of these mixed modes probing the core could reach substantial amplitudes at the surface (3, 4). The observed power spectrum of KIC 6928997 is in agreement with predicted spectra of such densely populated core-probing mixed modes. The lifetimes of these mixed modes must be longer than those of pure acoustic modes (1), because their mode broadening from damping is not yet fully resolved in the power spectrum (6). This is consistent with the predictions (3, 4).

The observed period spacings of the mixed modes of KIC 6928997, that is, the distance in period between modes of consecutive radial order, are shown in Fig. 1B. The spacings of dipole modes lead to a characteristic shape, which is understood from theory as a consequence of the interaction between the acoustic and gravity

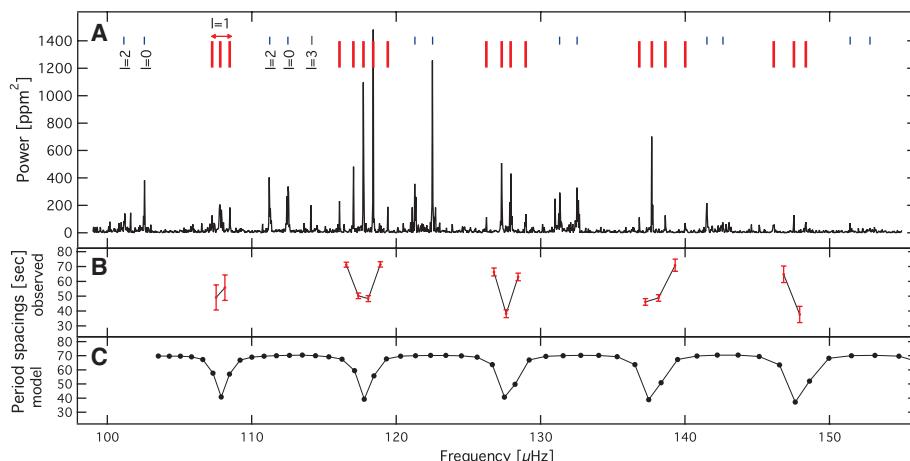


Fig. 1. (A) Oscillation spectrum and (B) corresponding period spacings of mixed $\ell = 1$ modes for the red-giant star KIC 6928997 as observed by the Kepler satellite. The position of the radial and quadrupole acoustic modes ($\ell = 0$ and 2) is indicated in blue, $\ell = 3$ in black, and the fine structure of the mixed modes in red ticks. ppm, parts per million; error bars in (B) indicate the uncertainty of the observed period spacings. (C) Adiabatic period separations for $\ell = 1$ modes derived from a stellar model similar to KIC 6928997 (6).

mode cavities for such modes (fig. S2) and is a key indicator of the core properties. There is a good qualitative agreement between our observations (Fig. 1B) and the pattern of theoretically predicted spacings for an appropriate stellar model (Fig. 1C). The observed period spacing, along with its detected characteristic structure, provide a lower bound for the constant period spacing, which is directly dependent on the density contrast between the core region and the convective envelope.

References and Notes

1. J. De Ridder *et al.*, *Nature* **459**, 398 (2009).
2. T. R. Bedding *et al.*, *Astrophys. J.* **713**, L176 (2010).
3. M.-A. Dupret *et al.*, *Astron. Astrophys.* **506**, 57 (2009).
4. J. Montalbán, A. Miglio, A. Noels, R. Scuflaire, P. Ventura, *Astrophys. J.* **721**, L182 (2010).
5. W. J. Borucki *et al.*, *Science* **327**, 977 (2010); 10.1126/science.1185402.
6. Materials and methods are available as supporting material on Science Online.
7. We acknowledge the work of the team behind Kepler. Funding for the Kepler mission is provided by NASA's Science Mission Directorate. We received funding from the European Community's 7th Framework Programme, European Research Council grant no. 227224 (PROSPERITY). All authors thank their national funding agencies.

Supporting Online Material

www.sciencemag.org/cgi/content/full/science.1201939/DC1
Materials and Methods
Figs. S1 and S2
References

20 December 2010; accepted 8 February 2011

Published online 17 March 2011;

10.1126/science.1201939

¹Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, 3001 Leuven, Belgium. ²Sydney Institute for Astronomy, School of Physics, University of Sydney, Sydney, NSW 2006, Australia. ³Laboratoire d'études spatiales et d'instrumentation en astrophysique, CNRS, Université Pierre et Marie Curie, Université Denis Diderot, Observatoire de Paris, 92195 Meudon, France. ⁴Laboratoire Astrophysique, Instrumentation, et Modélisation, Commissariat à l'Energie Atomique/Direction des Sciences de la Matière-CNRS-Université Paris Diderot, L'institut de recherche sur les lois fondamentales de l'univers/Service d'Astrophysique, Centre de Saclay, 91191 Gif-sur-Yvette, France. ⁵Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada. ⁶University of Birmingham, Birmingham B15 2TT, UK. ⁷Astronomical Institute, University of Amsterdam, Post Office Box 94249, 1090 GE Amsterdam, Netherlands. ⁸Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark. ⁹Institute for Mathematics, Astrophysics, and Particle Physics, Department of Astrophysics, Radboud University, NL-6500 GL Nijmegen, Netherlands. ¹⁰Institut d'Astrophysique et Géophysique, Université de Liège, 4000 Liège, Belgium. ¹¹Space Telescope Science Institute, Baltimore, MD 21218, USA. ¹²Las Cumbres Observatory Global Telescope, Goleta, CA 93117, USA. ¹³Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA. ¹⁴High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO 80307, USA. ¹⁵SETI Institute/National Aeronautics and Space Administration (NASA) Ames Research Center, M/S 244-30, Moffett Field, CA 94035, USA.

*To whom correspondence should be addressed. E-mail: paul.beck@ster.kuleuven.be